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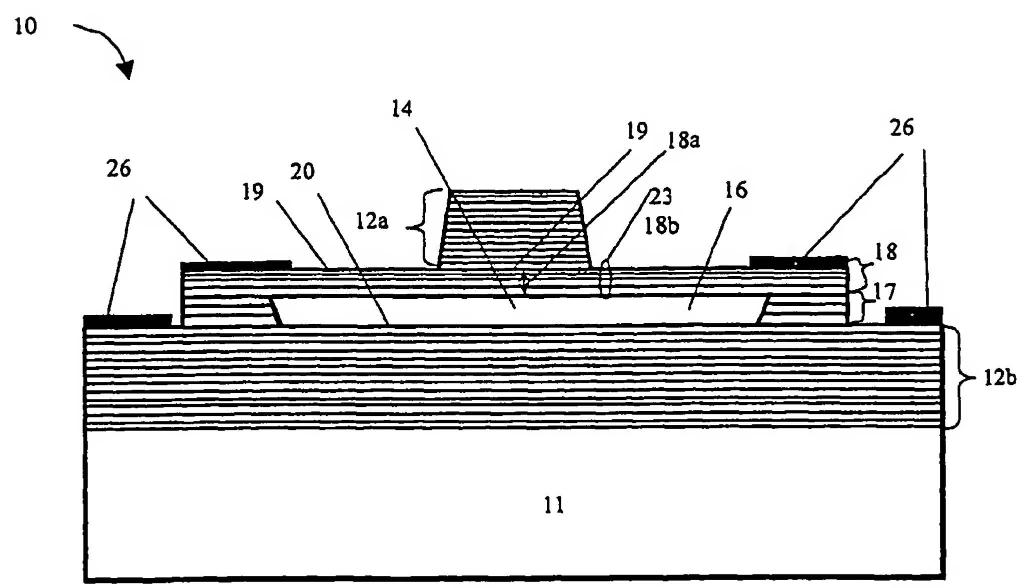
[Continued on next page]

(54) Title: A MICRO-ELECTROMECHANICALLY TUNABLE VERTICAL CAVITY PHOTONIC DEVICE AND A METHOD OF FABRICATION THEREOF



(57) **Abstract:** A tunable Fabry-Perot vertical cavity photonic device and a method of its fabrication are presented. The device comprises top and bottom semiconductor DBR stacks and a tunable air-gap cavity therebetween. The air-gap cavity is formed within a recess in a spacer above the bottom DBR stack. The top DBR stack is carried by a supporting structure in a region thereof located above a central region of the recess, while a region of the supporting structure above the recess and outside the DBR stack presents a membrane deflectable by the application of a tuning voltage to the device contacts.

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GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii)) for the following designations AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZM, ZW, ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG)*

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A Micro-electromechanically Tunable Vertical Cavity Photonic Device and a Method of Fabrication Thereof

FIELD OF THE INVENTION

The present invention is generally in the field of semiconductor optoelectronic devices, and relates to micro-electromechanically tunable vertical cavity photonic devices, such as filters and lasers, and a method of their fabrication.

BACKGROUND OF THE INVENTION

Tunable optical filters and tunable Vertical Cavity Surface Emitting Lasers (VCSELs) based on micro-electromechanical Fabry-Perot filter technology have recently generated considerable interest in the art. This is due to the fact that these devices present low cost alternatives to standard tunable filters, lasers and photodetectors which normally are high cost components, and for this reason, cannot be used in emerging wavelength division-multiplexing (WDM) local area networks systems which are very cost sensitive.

A micro-electromechanical tunable vertical cavity device operating in a specific wavelength range represents a Fabry-Perot cavity formed between two distributed Bragg reflectors (DBRs) that have high reflectivity values in this specific wavelength range. The Fabry-Perot cavity incorporates a tunable air gap cavity with a thickness of about a number of half-wavelengths. Normally, the top DBR is suspended on a micro-mechanical cantilever (or a number of micro-beams) above the air gap and can be deflected by changing the electric field in the air-gap cavity. This changes the wavelength of resonance of the Fabry-Perot cavity. The higher the reflectivity of the DBRs, the narrower the linewidth of the transmission wavelength in a tunable filter. Lower threshold gain and higher selectivity are achieved, respectively, in tunable VCSELs and resonant photodetectors.

Semiconductor based DBRs, which have low optical absorption, good thermal conductivity and reflectivity values in excess of 99.5%, are widely used in the art for the fabrication of different types of micro-electromechanically tunable vertical cavity devices.

US Patent 5771253*discloses a tunable VCSEL device based on the micro-electromechanical Fabry-Perot filter technology which comprises an electrically deflectable cantilever, a top and bottom DBR and a multiquantum well (MQW) region. The MQW well region is situated between a bottom DBR and a top reflector consisting of a partial DBR situated on top of the MQW, an air-gap and a moveable DBR situated on the cantilever. An oxide layer is situated in the partial DBR to provide lateral electrical and optical confinement in the active region.

The article "Widely and continuously tunable micromachined resonator cavity detector with wavelength tracking",* M.S. Wu, E.S. Vail, G.S. Li, W. Yuen and C.J. Chang-Hasnain, IEEE Photon. Technol. Lett., **8**, (1996), No 1, pp. 98-100, discloses a tunable photodetector based on the micro-electromechanical Fabry-Perot filter technology which comprises an electrically deflectable cantilever, top and bottom DBR stacks and a photodetector region situated between top and bottom DBRs.

The article "GaAs Micromachined Widely Tunable Fabry-Perot Filters",* E.C. Vail et al., Electronics Letters Online, Vol. 31, No. 3, 1995, pp. 228-229, discloses a process of fabrication of a tunable optical filter of the kind specified. First, a monolithic structure is formed consisting of top and bottom DBRs separated by a sacrificial layer. Then, the top DBR is structured by etching it completely in unmasked regions until reaching the sacrificial layer. This process is followed by selectively etching the sacrificial layer in unmasked regions and under the top DBR and supporting cantilever. This results in that the top DBR is suspended above the bottom DBR and in an air gap between the top and bottom DBRs having a thickness approximately equal to the thickness of the sacrificial layer. The remaining part of the sacrificial layer fixes the cantilever at its base.

All cantilever-based devices have a complex fabrication process and are mechanically unstable, which results in a low fabrication yield. These devices are also difficult to optimize: if the cantilever is longer than 100μm, the mechanical instability drastically increases. In case of shorter cantilevers, the flexibility is reduced, resulting in the necessity to decrease their thickness. This results in the reduction of the number of pairs in the top DBR stack, and consequently, in inferior device parameters.

A different technique of fabrication of an electrically tunable optical filter is disclosed in US Patent No. 5,739,945 and in the article "Widely Tunable Fabry-Perot Filter Using Ga(Al)As-AlO_x Deformable Mirrors", P. Tayebati et al., IEEE Photonics Technology Letters, Vol. 10, No. 3, 1998, pp. 394-396. According to this technique, the low index AlGaAs layers of a conventional mirror stack consisting of GaAs and AlGaAs layers is substituted with oxidized AlGaAs layers or air gaps. Although this technique provides quite good results, i.e., the tuning range of 70nm around 1.5μm was obtained by applying a voltage of 50V, the fabrication process is very complex and the device structure obtained with this technique is even more mechanically unstable than standard cantilever-type devices.

SUMMARY OF THE INVENTION

There is accordingly a need in the art to improve micro-electromechanically tunable vertical cavity photonic devices by providing a novel device structure and fabrication method.

The main idea of the present invention consists in replacing cantilevers and beams which support top DBRs in the prior art devices of the kind specified by a membrane, which completely covers an air-gap cavity and carries the top DBR stack, which is situated in the center of the membrane. The air-gap is incorporated in an etched-through recess in a spacer which is blocking the current flow when applying a voltage to the device contacts to deflect the membrane. Membrane

deflection results in tuning the air-gap cavity and, as a consequence, the resonance wavelength of the device.

The above is implemented in the following manner: First, the surface of a spacer is structured by etching a recess through it. Then, a supporting structure, on which a DBR is located, is bonded to the structured surface of the spacer. This is followed by etching the DBR till reaching the supporting region, thereby forming a mesa of the top DBR stack. The mesa is centered around a vertical axis passing through the center of the recess and has the lateral dimension less than that of the recess. A region of the supporting structure outside the top DBR stack (mesa) and above the recess presents the membrane.

The membrane is, on the one hand, very flexible (having the thickness of about 1μm), and, on the other hand, is continuous in the lateral direction, and is therefore mechanically stable, resulting in a high fabrication yield. The top DBR can be made of a large number of layers without affecting the flexibility of the membrane and providing a narrow linewidth of transmitted light. By forming an island of high refractive index material in the way of the optical beam inside the optical cavity of the device, the position of the beam during the tuning process is stabilized.

Thus, according to one aspect of the present invention, there is provided a Fabry-Perot tunable vertical cavity device comprising top and bottom semiconductor DBR stacks separated by a tunable air-gap cavity and a supporting structure that carries the top DBR stack, wherein the air-gap cavity is located within a recess formed in a spacer completely covered by the supporting structure, the top DBR stack being centered around a vertical axis passing through the center of said recess and having a lateral dimension smaller than the lateral dimension of the recess, a region of the supporting structure above the recess and outside the top DBR stack presenting a membrane to be deflected by application of a tuning voltage to electrical contacts of the device.

According to another aspect of the present invention, there is provided a method of fabrication of a Fabry-Perot tunable vertical cavity device comprising

top and bottom DBR stacks with a tunable air-gap cavity therebetween, the method comprising the steps of:

(i) forming a spacer above the bottom DBR stack;

(ii) fabricating an etched-through recess in the spacer, thereby forming a structured surface of the spacer, said recess presenting a location for said tunable air-gap cavity;

(iii) bonding a top DBR wafer including a supporting structure to the structured surface of the spacer in such a way that said supporting structure faces said structured surface of the spacer and completely covers said recess, thus forming the air-gap cavity, and selectively etching a substrate on which layers of the top DBR were grown;

(iv) forming the top DBR stack above a central region of said recess and a membrane above said recess outside said top DBR stack, by etching the layers of the top DBR till reaching the supporting structure so as to define a mesa presenting said top DBR stack having a lateral dimension smaller than the lateral dimension of said recess and being centered about a vertical axis passing through the center of said recess, a region of the supporting structure above said recess and outside said mesa presenting said membrane deflectable by application of a tuning voltage to electrical contacts of the device.

In order to confine the optical mode of transmitted or emitted light, a mesa can be formed on the bottom of the recess being centered around the vertical axis passing through the center of the recess and having the lateral size of less than 10 and height of less than 1/30 of the device operation wavelength.

The spacer region can be placed on top of the bottom DBR, in which case the device presents a tunable optical filter. In the case of tunable VCSELs and tunable resonant photodetectors, an active cavity material is placed between the spacer and the bottom DBR.

The top DBR stack may comprise pairs of layers of $Al_xGa_{1-x}As$ with different values of x, and the supporting structure and the bottom DBR stack may

also comprise the same pairs of layers as in the top DBR stack. The spacer may comprise layers with alternating n-type and p-type doping. In the case of the tunable filter, the spacer may comprise the same pairs of layers as in the bottom DBR with alternating n- and p-type doping. In the case of tunable VCSELs and tunable resonant photodetectors, the spacer may comprise layers grown in the same material system as layers in the active cavity material stack with alternating n- and p-type doping.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the invention and to see how it may be carried out in practice, several embodiments will now be described, by way of non-limiting examples only, with reference to the accompanying drawings, in which:

Fig. 1 illustrates an example of a tunable optical filter device according to the present invention;

Fig. 2 illustrates the fabrication of the filter device of Fig. 1;

Fig. 3 illustrates an example of a tunable VCSEL device according to the present invention; and

Figs. 4 and 5 illustrate the fabrication of the tunable VCSEL device of Fig. 3.

DETAILED DESCRIPTION OF THE INVENTION

Referring to Fig. 1, there is schematically illustrated a tunable vertical cavity device, generally designated **10**, constructed according to one embodiment of the present invention. The device **10** is designed like a Fabry-Perot vertical cavity based device, having two semiconductor DBRs **12a** and **12b**, and an air-gap cavity **14** therebetween, and presents a tunable optical filter. The air-gap cavity **14** is located within an etched-through recess **16** formed in a spacer **17**, which is located on top of the bottom DBR **12b** and is completely covered by a supporting structure **18**, which carries the top DBR stack **12a**. The top DBR stack **12a** is located on a region **18a** of the supporting structure **18** so as to be centered around a vertical axis

13. The method according to Claim 8, and also comprising formation of an active cavity material between the bottom DBR stack and the spacer.

14. The method according to Claim 13, wherein the formation of the active cavity material comprises the steps of growing a multiquantum well layer stack sandwiched between two cladding layers.

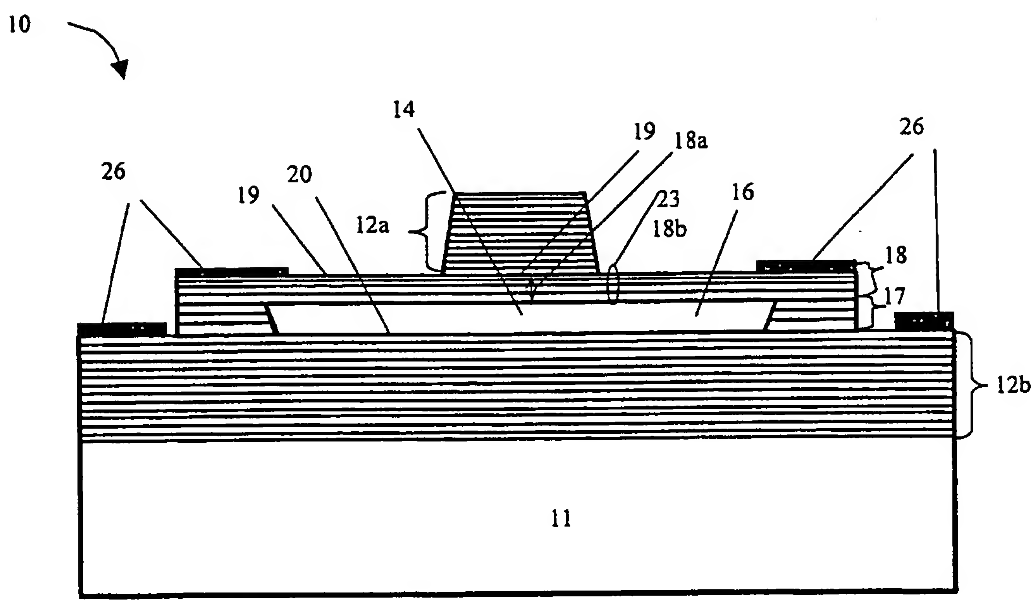

Fig. 1.

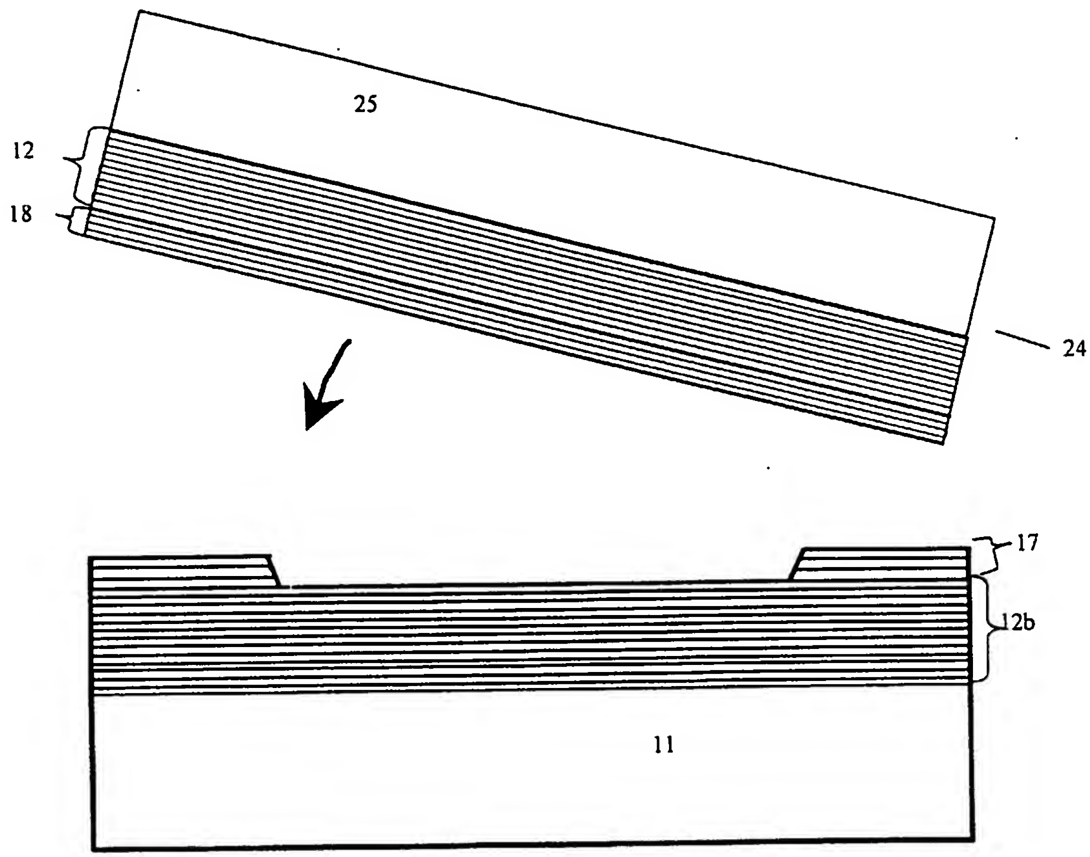

Fig. 2.

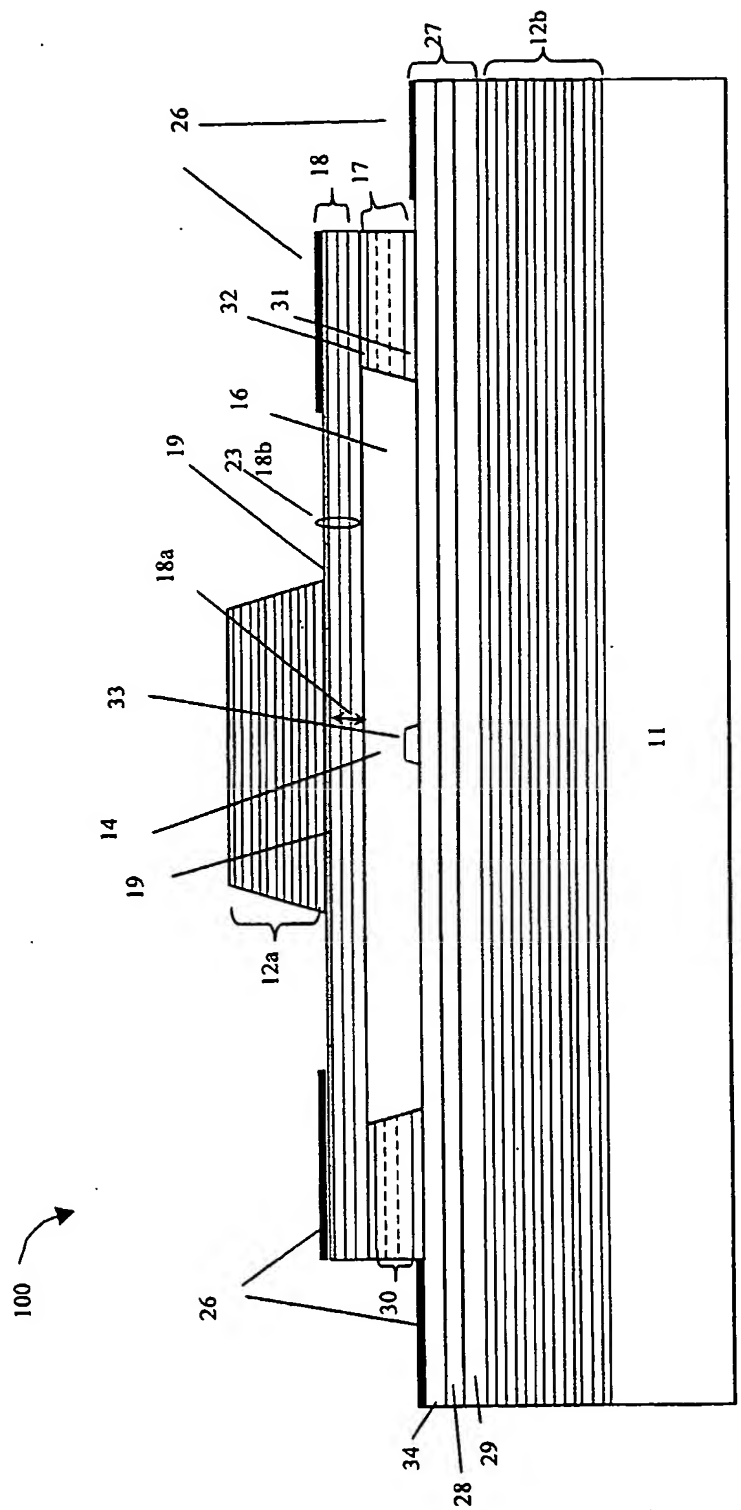
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Fig. 3.

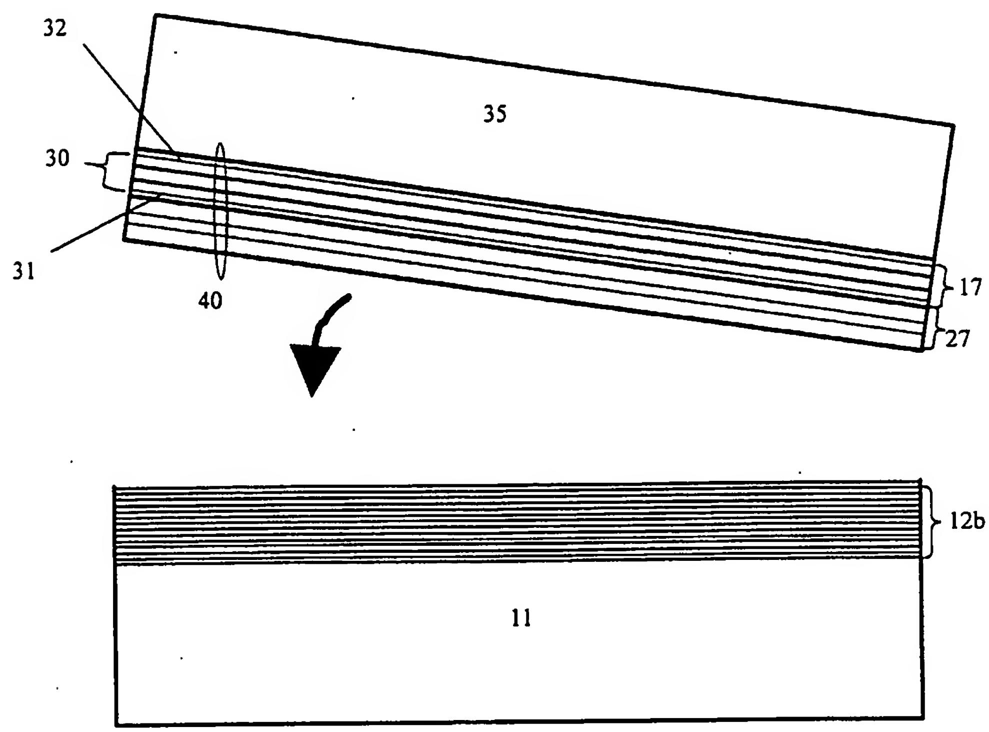

Fig. 4.

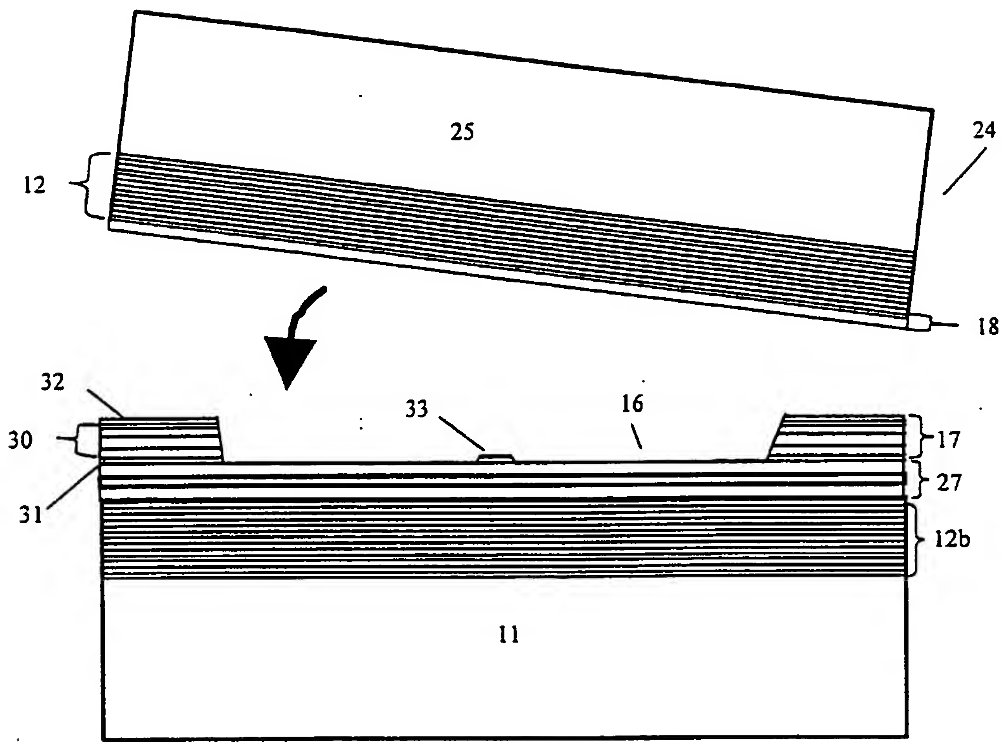

Fig. 5.

INTERNATIONAL SEARCH REPORT

Intern	il Application No
PCT/IB 02/00682

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01J3/26 H01S5/183 H01S5/187

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01J H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 99 34484 A (CORETEK INC) 8 July 1999 (1999-07-08) page 10, line 1 -page 17, paragraph 2 page 34, paragraph 1 -page 40, paragraph 1 figures 1,3F,4G,6-8 ---	1,8
A	US 5 739 945 A (TAYEBATI PARVIZ) 14 April 1998 (1998-04-14) cited in the application column 7, line 19 - line 32 figure 7 ---	1,8
A	US 5 142 414 A (KOEHLER DALE R) 25 August 1992 (1992-08-25) column 4, line 27 - line 50 figure 3 --- -/--	1,8

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
11 July 2002	22/07/2002

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Jacquin, J

Intern Application No
PCT/IB 02/00682

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CORREIA J H ET AL: "Bulk-micromachined tunable Fabry-Perot microinterferometer for the visible spectral range" SENSORS AND ACTUATORS A, ELSEVIER SEQUOIA S.A., LAUSANNE, CH, vol. 76, no. 1-3, 30 August 1999 (1999-08-30), pages 191-196, XP004184436 ISSN: 0924-4247 figure 1 -----	1,8

INTERNATIONAL SEARCH REPORT

Information on patent family members

Intern: Application No
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